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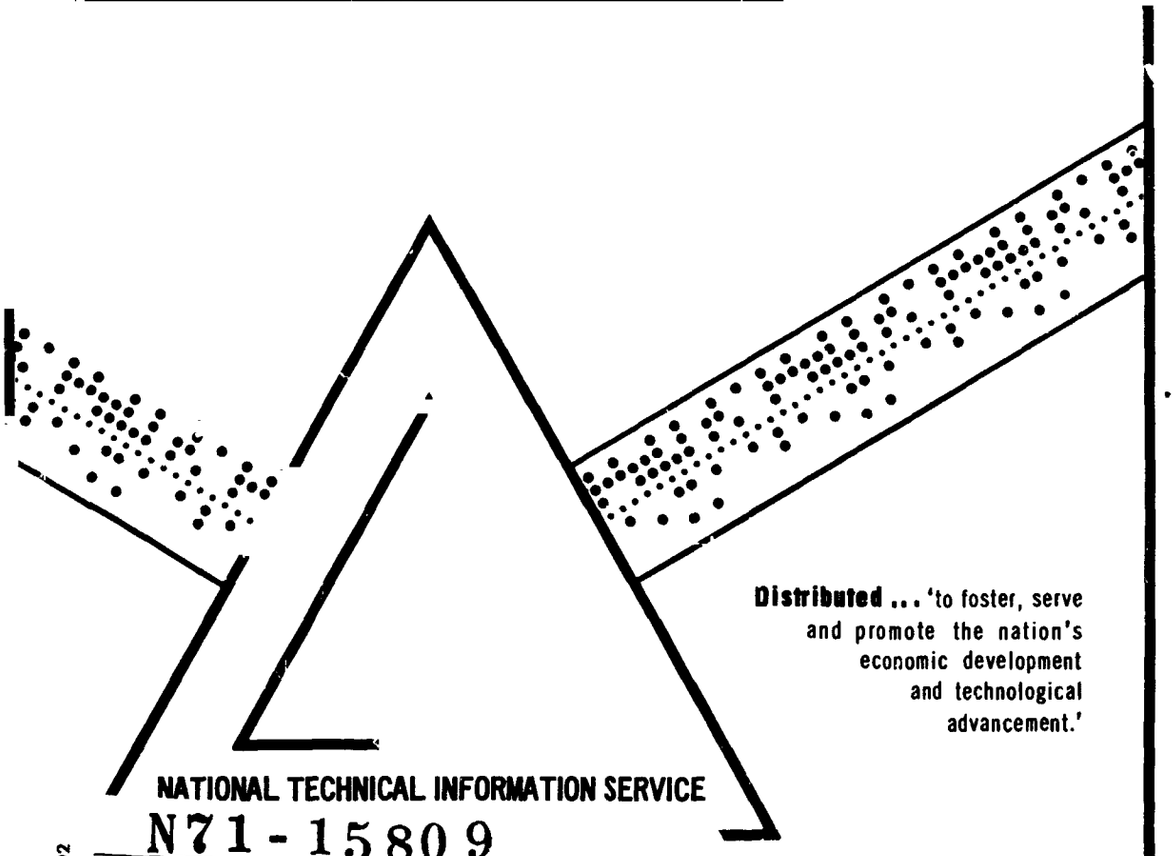

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CAVITATION IN LIQUID CRYOGENS*

D. K. Edmonds and J. Hord

NBS Institute for Basic Standards
Boulder, Colorado

INTRODUCTION

Cavitation is usually defined as the formation, caused by a reduction in pressure, of a vapor phase within a flowing liquid, or at the interface between a liquid and a solid surface. For incipient cavitation, this definition is somewhat ambiguous because various criterion and methods are used to detect the vapor phase. Incipient cavitation usually refers to the fluid condition where the vapor phase is barely visible to the unaided eye. The visual inception criterion is used because the sensitivity [1-3] of various acoustic detectors can vary appreciably. Pressure and temperature profiles within fully developed cavities recently were measured [4] and are referred to herein as developed-cavitation data.

To design liquid handling equipment such as pumps and flow meters, the designer must determine whether cavitation will occur, and in many cases, to what extent. While the noncavitating performance of hydraulic equipment may be predicted from established similarity laws, cavitating performance can seldom be predicted from fluid to fluid. The effects of fluid properties on cavitation performance are well recognized [5-14] and require more understanding to develop improved similarity relations [15] for equipment design. NASA has undertaken a program [16] to determine the thermodynamic behavior of different fluids in an effort to obtain improved design criteria to aid in the prediction of cavitating pump performance. The experimental data described herein were obtained in support of this program and represent an extension of work done at NASA [15-22]. The purpose of this presentation is twofold: (a) to briefly review key experimental results reported elsewhere [4], and (b) to propose and evaluate possible improvements to existing theory regarding the effects of fluid properties on developed-cavitation performance of equipment. The analytical part of this work extends the similarity equation [15] by permitting the cavity thickness l to vary as a function of velocity and cavity length. The cavity thickness was taken as constant in the previous study [15].

The similarity equation is useful for correlating the cavitating performance [15, 16] of a particular piece of equipment from fluid to fluid; this equation is also useful in extending the velocity and temperature range of data for any given fluid. Experimental data [4] were used to evaluate the postulated improvements, theory, etc., concerning this similarity equation. The test section was a transparent plastic venturi with a quarter-round throat entrance. Details of the venturi, apparatus, operating procedure, etc., are given elsewhere [4].

*Experimental work performed under the sponsorship of NASA Lewis Research Center under Contract No. C-[illegible]-A.

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REVIEW OF EXPERIMENTAL DATA

Figure 1 presents typical* cavity pressure-depression curves for liquid hydrogen; Fig. 2 shows similar data for nitrogen. "Pressure depression" refers to the difference between saturation pressure at inlet temperature and measured cavity pressure. Cavity temperature measurements have been converted into equivalent saturation pressures,

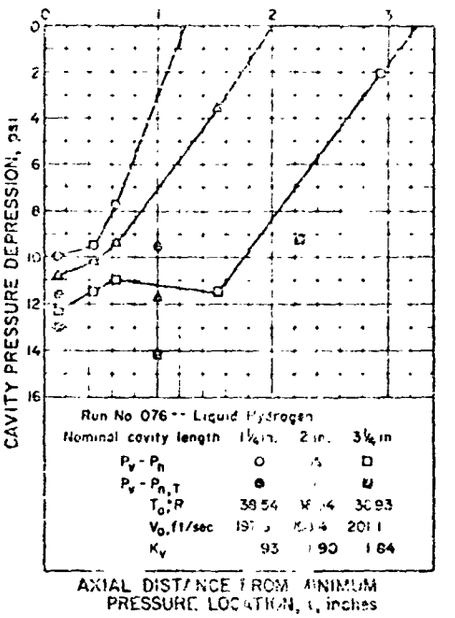

Fig. 1. Typical pressure depressions within cavities in liquid hydrogen.

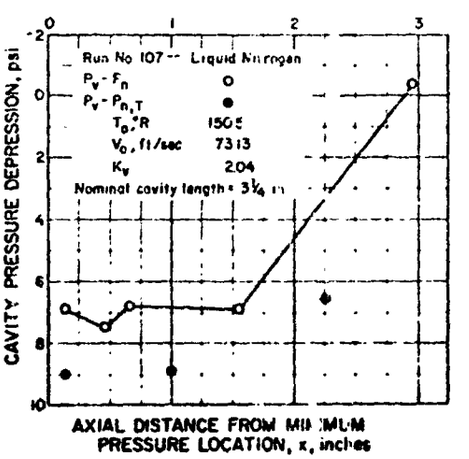

Fig. 2. Typical pressure depressions within a cavity in liquid nitrogen.

*More graphical and tabulated developed-cavitation data are given elsewhere [*].

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[illegible] these figures for comparison [illegible] pressure [illegible] pressure is plotted as a function of distance [illegible] the test section throat. Note [illegible] lower than the vapor pressure of the [illegible] 651 ft of hydrogen head and 4[illegible] ft of nitrogen head). In [illegible] developed [illegible] tests, the measured cavity pressure exceeded [illegible] to the measured cavity temperature by an amount which could not be attributed to errors in pressure and temperature measurements. Also, examination of the data revealed that the degree of metastability in the cavity appeared to be a function of bulk-stream liquid temperature, velocity, and axial position within the cavity. It was concluded therefore that, in general, the pressures and temperatures within the cavity are not in thermodynamic equilibrium.

A series of photographs of developed cavitation in liquid nitrogen are shown in Fig. 3; the porosity of the nitrogen cavities usually decreases with increasing velocity or increasing temperature. These photographs are representative of conditions at which data were reduced. Similar photographs of hydrogen cavities are not shown because the cavities are nonporous and uniform in structure [1].

EXTENSION OF THE CAVITATION SIMILARITY EQUATION THEORY*

The similarity equation for developed cavitation is given by Gelder *et al.* [15] as

$$B = B_{\mathrm{ref}} \left[\left(\frac{\alpha_{\mathrm{ref}}}{\alpha} \right) \left(\frac{l_{\mathrm{ref}}}{l} \right) \left(\frac{V_0}{V_{0,\mathrm{ref}}} \right) \right]^{0.5} \left(\frac{\bar{t}}{\bar{t}_{\mathrm{ref}}} \right) \tag{1}$$

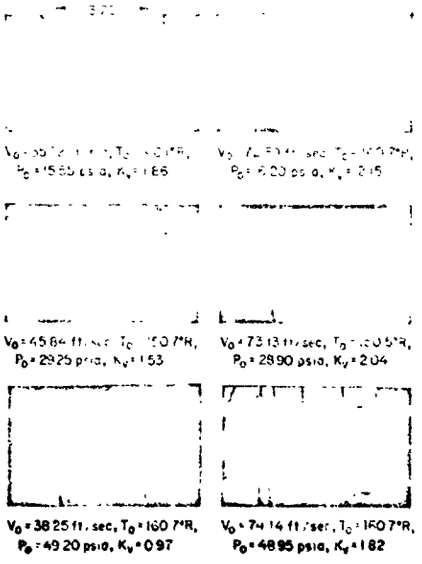

Fig. 3. Effects of velocity and temperature on the appearance of developed cavities in liquid nitrogen; nominal cavity length, 3.25 in.

***Applications of the similarity equation are described in the introduction to this paper and in the literature [15, 16, 24].**

where B is the volume of vapor in the cavity divided by the volume of liquid from which heat has been vaporized (during evaporation) or formed (during condensation). B can also be obtained from a theoretical expression relating cavity pressure depression to "B" factor; this theoretical value is called B_t. B_t is derived from an energy balance between the vapor and the coordinate liquid film at the liquid-vapor interface. The main assumptions used to derive B_t have been studied by several authors [14] and are summarized by Gelder *et al.* [15].

To account for the difference between theory and practice, (1) can be written in the following form:

$$B = B_{\text{ref}} \left(\frac{\alpha_{\text{ref}}}{\alpha}\right)^m \left(\frac{l_{\text{ref}}}{l}\right)^n \left(\frac{V_0}{V_{0,\text{ref}}}\right)^p \left(\frac{\bar{l}}{\bar{l}_{\text{ref}}}\right) \tag{2}$$

The exponents in (2) are evaluated from experimental data as follows:

1. B_t is obtained for each experimental data point from a cavity pressure-depression ($p_v - p_n$) vs. "$\bar{l}$" factor plot [15].

2. One data point is arbitrarily chosen as a reference; the α, l, V_0, and B_t from the chosen experimental run are then inserted into (2) as constants where the subscript "ref" occurs. The $\bar{l}$ term can be considered equal to unity (as in previous studies [4, 15]) or a function of cavity length l and velocity V_0 (see discussion below); in the latter case, the $\bar{l}$ term is absorbed into the l and V_0 terms.

3. Values of α, l, and V_0 from each data point are then inserted into (2) as the non-subscripted terms. This produces an equation for every data point except the one chosen as a reference. Note that the unknowns in this set of simultaneous equations are B and the exponents m, n, and p.

4. The computer is then programmed to range through values of the exponents—one at a time. For each new value of m, n, or p the computer finds the value for B, on the left side of (2), then computes the sum of the squares of the differences between the calculated B and the B_t for each equation. The computer adjusts the exponents until the sum of the squares of the differences are minimized; in some cases, one or more exponents were held constant at theoretical or arbitrary values. This process ensures that the calculated B values are brought as closely as possible to their respective theoretical B_t values; the exponents computed in this manner represent the best agreement between experiment, equation (2), and the energy balance equation for B_t.

In the work of Gelder *et al.* [15], the cavity thickness ratio in (2) was assumed to be unity and the exponents for the other terms were experimentally evaluated. The exponents obtained by Gelder *et al.* for F-114, along with the theoretical exponents for (1), were applied to the data obtained in recent experiments [4]. The "best fit" set of exponents were also obtained by computer for these data, again assuming the $\bar{l}$ term equal to unity. Tables of exponents, along with their standard deviations in the B factor, are given in Table I for hydrogen and Table II for nitrogen. The standard deviation is a measure of the validity of the theories for the similarity and B_t expressions as both are evaluated from experimental data. The numerical value of B_t usually lies between two and five.

Because the "best fit" exponents vary appreciably from the theoretical values, one possibility for improvement is to let $\bar{l}$ be a function of cavity length and velocity. As an example, assume that the cavity has the shape of a semicubical parabola, $t^3 = ax^2$; if it is also assumed that the coordinate proportionality factor is linearly related to V_0, then

$a = kV_0x$ where k is constant for any given fluid and test item. Obtaining the expression for $\bar{t}$ requires an integration

$$\bar{t} = \frac{1}{l}\int_0^l (kV_0)^{1/3}x^{2/3}\,dx \tag{3}$$

Integration of (3) and substitution of the resulting $\bar{t}$ into (1) results in

Table I. Evaluation of Similarity Equation Using Liquid Hydrogen Data

Data identification	Source of exponents (i.e., assumed cavity shapes from this paper and exponents obtained from reference material)		Exponents‡			Standard deviations† using reference cavity lengths as follows:		
			m	n	p	1.25 in.	2.00 in.	3.25 in.
T 1-1	Theory [15]; See (1)	$\bar{t} = \bar{t}_{ref}$	0.5	0.5	0.5	1.64	1.36	2.22
T 1-2	Gelder, *et al.* [15], experimental data with F-114		0.5	−0.16	0.85	0.83	0.92	0.67
T 1-3	Computer "best fit"		0.5	0.5	0.314*		1.33	
T 1-4			0.5	−0.278*	0.5			0.58
T 1-5			0.5	−0.332*	0.5		0.58	
T 1-6			0.5	−0.372*	0.5	0.56		
T 1-7			0.5	−0.308*	0.732*			0.56
T 1-8			0.5	−0.348*	0.446*		0.57	
T 1-9			0.5	−0.39*	0.61*	0.56		
T 1-10			−3.52*	−0.348*	0.554*			0.38
T 1-11			−3.82*	−0.304*	0.644*		0.36	
T 1-12			−3.82*	−0.414*	0.496*	0.41		
T 1-13			−4.62*	0.5	0.5		1.17	
T 1-14	Exponents chosen as a compromise between theory and experiment	$\bar{t} = \bar{t}_{ref}$	0.5	−0.3	0.5	0.59	0.58	0.58
T 1-15	Semi-cubical parabola	$t^3 = kx^2$	0.5	−0.167	0.5	0.74	0.63	0.62
T 1-16	Concave parabola	$t^2 = kx$	0.5	0	0.5	0.98	0.76	0.84
T 1-17	Straight line	$t = kx$	0.5	−0.5	0.5	0.66	0.63	0.71
T 1-18	Semi-cubical parabola	$t^3 = kV_0x^2$	0.5	−0.167	0.833	0.82	0.89	0.65
T 1-19	Concave parabola	$t^2 = kV_0x$	0.5	0	1.0	1.11	1.23	0.99
T 1-20	Straight line	$t = kV_0x$	0.5	−0.5	1.5	0.77	2.49	0.78

‡$B = B_{ref}\left(\frac{\alpha_{ref}}{\alpha}\right)^m \left(\frac{l_{ref}}{l}\right)^n \left(\frac{V_0}{V_{0,ref}}\right)^p$

†Standard Deviation = $\sqrt{[\Sigma(B-B_t)^2]/N}$ where N = number of data points, B_t is computed from theory [15], and B is computed from (2).

*Exponents selected by computer, from experimental data, using a "least squares" fitting technique.

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Table II Evaluation of Similarity Equation Using Liquid Nitrogen Data

Data identification	Source of exponents		Exponents‡ m	Exponents‡ n	Standard deviations† using 3.25 in cavity as reference
T2-1	Theory [15], see (3)	$l = l_{ref}$	0.5	0.5	0.515
T2-2	Gelder, *et al.* [19] experimental data with F-114		0.5	0.85	0.671
T2-3	Computer "best fit"		0.5	0.385*	0.533
T2-4	Computer "best fit"		−1.22*	0.492*	0.498

‡$B = B_{ref}\left(\frac{\alpha_{ref}}{\alpha}\right)^{m}\left(\frac{l}{l_{ref}}\right)^{n}\left(\frac{V_0}{V_{0,ref}}\right)^{p}$

†Standard Deviation = $\sqrt{[\Sigma(B-B_i)^2]/N}$ where N = number of data points, B_i is computed from theory [15], and B is computed from (2).

*Exponents selected by computer, from experimental data, using a "least squares" fitting technique.

$$B = B_{ref}\left(\frac{\alpha_{ref}}{\alpha}\right)^{0.5}\left(\frac{l_{ref}}{l}\right)^{-0.167}\left(\frac{V_0}{V_{0,ref}}\right)^{0.833}\left(\frac{k}{k_{ref}}\right)^{0.333} \tag{4}$$

The $(k/k_{ref})^{0.333}$ term is taken as unity in (4) because the similarity equation requires geometrically similar cavity shapes from fluid to fluid for a specific test item; also, correlations* between fluids are not being evaluated in this study. Other basic geometrical cavity shapes can be assumed and different exponents for the l and V_0 terms will result. Table I lists the standard deviation in B factor resulting from the use of several assumed cavity shapes, as applied to the liquid hydrogen cavitation data obtained from recent experiments. The cavity thickness may also be treated as a function of cavity length, but independent of velocity. In this case $t^q = kx^w$ where q and w depend only upon the assumed cavity geometry, e.g., $q = w = 1$ for a straight-line variation, etc. Computer results for some basic cavity shapes (neglecting effect of velocity on cavity thickness) are also given in Table I.

DISCUSSION OF RESULTS

Developed-cavitation data for nitrogen were obtained for one cavity length only; therefore, the postulations concerning cavity shape could only be applied to the hydrogen data where three cavity lengths were available. Examination of Table I shows that the basic theory (data set T1-1) gives rather poor results in terms of the standard deviation. Better results are obtained by using the exponents of Gelder *et al.*, (data set T1-2) or by permitting the computer to select one or more of the exponents (T1-3 through T1-13); of course, the best fit exponents in sets T1-10 through T1-12 give the best results.†

In Table I, three different cavity lengths were used as references in order to determine the effect of reference length upon standard deviation. The exponents $m = 0.5$, $n =$

*Limited nitrogen data precluded correlation between nitrogen and hydrogen fluids. NASA Lewis Research Center personnel are preparing computer correlations [25] using available hydrogen and F-114 data.

†Standard deviation is minimized in those computations where one or more exponents are selected by the computer; the absolute minimum standard deviation is obtained by permitting the computer to select all three exponents.

$= 0.3$, and $p = 0.5$ (see data set T1-14) were least affected by reference cavity length; note that these exponents produce a low standard deviation. In general, the 2.0 and 3.25 in. cavities provided the lowest standard deviations. Note that the exponent p is theoretically 0.5 for all cavity shapes assumed to be independent of velocity (T1-15, T1-16, and T1-17); also p tends to 0.5 when all three exponents are allowed to seek a best fit (T1-10, T1-11, and T1-12 for hydrogen; T2-4 for nitrogen).

Table I shows that velocity-dependent cavity shapes (T1-18, T1-19, and T1-20) produce standard deviations that exceed those for cavity shapes where velocity is neglected (T1-15, T1-16, and T1-17). However, the semi-cubical parabola with a velocity-dependent shape (T1-18) does give almost the same exponents that Gelder *et al.*, obtained (T1-2) with F-114. Perhaps the concept of velocity-dependent cavity shape is pertinent for some fluids other than hydrogen. The assumption that average cavity thickness is a function of cavity length indicates considerable promise for hydrogen; the semi-cubical parabola (T1-15) and the straight line (T1-17) shapes give the best results of the three cavity shapes examined here.

The lack of variation in $\alpha(< 10\%)$ may explain why the exponent m tends to a negative number (T1-10 through T1-13 for hydrogen, and T2-4 for nitrogen); because the standard deviation is barely affected by this small variation in α, m was usually held at the theoretical value of 0.5.

SUMMARY

Some characteristic data for developed cavitation in both hydrogen and nitrogen are given in the form of pressure-depression curves. These curves show that the pressure and temperature in the cavity are generally not in thermodynamic equilibrium.

Recent data are used to analyze and evaluate the basic similarity-equation theory and to compare these results with the experimental work of others; the cavity thickness ratio is assumed to be unity.

An analytical method, to account for variations in cavity thickness, is proposed and evaluated using the experimental hydrogen data; the results are again compared with the experimental work of others. The proposed method holds some promise for improvement of the cavitation similarity equation.

RECOMMENDATIONS FOR FUTURE WORK

More developed-cavitation data, using closely spaced pressure and temperature taps, is needed to ascertain more precisely the cavity pressure profile and fluid metastability.

All existing developed-cavitation data, including Gelder *et al.* should be computer correlated in order to determine the pertinency of assumptions concerning cavity shape; these correlations would use the existing "static-model" theory. Experiments should be designed to indicate the general shape of the cavity, thereby putting the theory on a firmer basis. An analysis should be performed to redevelop the cavity model, accounting for dynamic effects. Existing data could be used to evaluate the results of this analysis.

NOTATION

a = coordinate proportionality factor in cavity shape equations
B = ratio of vapor to liquid volume associated with the formation and sustenance of a fixed cavity in a liquid
g = gravitational acceleration, ft/sec^2
h_0 = test-section inlet head corresponding to absolute inlet pressure, ft
h_v = head corresponding to saturation pressure at the test section inlet temperature, ft
k = constant used in expression for cavity thickness t

K_F = fully developed cavitation parameter, $[(h_0-h_v)/(V_0^2/2g)]$
l = total cavity length measured from maximum-pressure point on quarter-round contour along axis of plastic venturi
P_v = absolute cavity pressure measured at a particular station or instrument port in wall of plastic venturi
$P_{v,T}$ = saturation pressure corresponding to the measured cavity temperature at a particular station or instrument port in wall of plastic venturi
P_0 = test-section absolute inlet pressure
P_v = saturation pressure at test-section inlet temperature
t = local thickness of vapor-filled cavity at any x value
$\bar{t}$ = average thickness of vapor-filled cavity
T_0 = bulk-stream temperature of liquid entering the test section, °R
V_0 = velocity of liquid at inlet to test section
x = distance measured from maximum-pressure point on quarter-round contour along axis of plastic venturi
α = thermal diffusivity of liquid

Subscripts

ref = reference test, or set of test conditions, to which a computation is being referenced when attempting to correlate cavitation performance via the similarity equation
t = denotes theoretical origin

Superscripts

m = exponent of thermal-diffusivity ratio in (2)
n = exponent of cavity-length ratio in (2)
p = exponent of test-section-inlet-velocity ratio in (2)
q = exponent in expression for cavity thickness
w = exponent in expression for cavity thickness

REFERENCES

1. C. P. Kittredge, "Detection and Location of Cavitation", Rept. MATT-142, Plasma Physics Lab., Princeton University, Princeton, N.J. (1962).
2. A. F. Lehman and J. O. Young, *ASME J. Basic Eng.*, 86:275 (1964).
3. J. W. Holl, ed., "Discussions – Symposium on Cavitation Research Facilities and Techniques," presented at Fluids Eng. Div. Conf., Philadelphia, Pa. (May 18–20, 1964).
4. J. Hord, D. K. Edmonds and D. R. Millhiser, "Thermodynamic Depressions Within Cavities and Cavitation Inception in Liquid Hydrogen and Liquid Nitrogen," NASA Rept. CR-72286 (1968).
5. J. Hord, R. B. Jacobs, C. C. Robinson, and L. L. Sparks, *ASME J. Eng. Power*, 86:485 (1964).
6. R. S. Brand, "The Motion of a Plane Evaporation Front in a Superheated Liquid," Tech. Rept. No. 2, University of Connecticut, Storrs, Conn. (1963).
7. J. A. Clark, "The Thermodynamics of Bubbles," Tech. Rept. No. 7, Massachusetts Institute of Technology, Cambridge, Mass. (1956).
8. J. W. Holl and G. F. Wislicenus, *ASME J. Basic Eng.*, 83:385 (1961).
9. M. C. Huppert, W. S. King, and L. B. Stripling, "Some Cavitation Problems in Rocket Propellant Pumps," presented at ASME Turbo Machinery Conf., Houston, Texas (1959); available from Rocketdyne, Canoga Park, Calif.
10. V. Ya. Karelin, "Cavitation Phenomena in Centrifugal and Axial Pumps," NASA accession No. N66-14532 (1963).
11. W. A. Spraker, *ASME J. Eng. Power*, 87:309 (1965).
12. A. J. Stepanoff, *ASME J. Eng. Power*, 86:195 (1964).
13. W. W. Wilcox, P. R. Meng, and R. L. Davis, in: ***Advances in Cryogenic Engineering, Vol. 8***, Plenum Press, New York (1953), p. 446.
14. A. Hollander, *ARS J.*, 32:1594 (1962).
15. **T. F. Gelder, R. S. Ruggeri, and R. D. Moore, "Cavitation Similarity Considerations Based on Measured Pressure and Temperature Depressions in Cavitated Regions of Freon 114", NASA TN D-3509 (1966).**
16. **I. I. Pinkel, M. J. Hartmann, C. H. Hauser, M. J. Miller, R. S. Ruggeri, and R. F. Soltis, "Pump Technology," NASA accession No. N66-33672 (1966).**

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.

17. R. S. Ruggeri and T. F. Gelder, *Advances in Cryogenic Engineering*, Vol. 9, Plenum Press, New York (1964), p. 304.
18. R. S. Ruggeri, private communication.
19. R. S. Ruggeri, R. D. Moore, and T. F. Gelder, "Incipient Cavitation of Ethylene Glycol in a Tunnel Venturi," NASA TN D-2772 (1965).
20. R. S. Ruggeri and T. F. Gelder, "Effects of Air Content and Water Purity on Liquid Tension at Incipient Cavitation in Venturi Flow," NASA TN D-1459 (1963).
21. R. S. Ruggeri and T. F. Gelder, "Cavitation and Effective Liquid Tension of Nitrogen in a Tunnel Venturi," NASA TN-2088 (1964).
22. T. F. Gelder, R. D. Moore, and R. S. Ruggeri, "Incipient Cavitation of Freon-114 in a Tunnel Venturi," NASA TN D-2662 (1965).
23. *Flow Measurement*, Chap. 4, Part 5, ASME, New York (1959), p. 17.
24. R. S. Ruggeri and R. D. Moore, "Method for Prediction of Pump Cavitation Performance in Various Liquids," to be published.
25. R. D. Moore and R. S. Ruggeri, "The Prediction of Thermodynamic Effects of Developed Cavitation Based on Liquid Hydrogen and Freon-114 Data in Scaled Venturis," to be published.

DISCUSSION

Question by R. Henry, NASA Lewis Research Center: Have you investigated the role of dissolved gases on the inception of the cavity, and if so how does this compare with the work of Hammitt at the University of Michigan?

Answer by author: No, we have not examined the effects of dissolved gases on cavitation inception; however, one of the advantages of experimenting with cryogenic liquids is the minimization of the effects of dissolved and residual gases upon nucleation. In our tests commercially available liquid cryogens, filtered to remove solid impurities, were transferred using condensible pressurants, (e.g., hydrogen gas over hydrogen liquid) to minimize these effects.